THE SPECTRA OF MAIN-SEQUENCE STARS IN GALACTIC GLOBULAR CLUSTERS. II. CH AND CN BANDS IN M71¹

JUDITH G. COHEN

Palomar Observatory, Mail Stop 105-24, California Institute of Technology, Pasadena, CA 91125

Received 1998 December 29; accepted 1999 January 25

ABSTRACT

Spectra with a high signal-to-noise ratio of 79 stars that are just below the main-sequence turnoff of M71 are presented. They yield indices for the strength of the G band of CH and the ultraviolet CN band at 3885 Å. These indices are each to first-order bimodal and they are anticorrelated. There are approximately equal numbers of CN-weak/CH-strong and CN-strong/CH-weak main-sequence stars in M71. It is not yet clear whether these star-to-star variations arise from primordial variations or from mixing within a fraction of individual stars as they evolve.

Key words: globular clusters: general — globular clusters: individual (M71) — stars: evolution

1. INTRODUCTION

The major issue I intend to explore in this series of papers is that of star-to-star variations in abundances within a single globular cluster at and below the level of the main-sequence turnoff. In the first paper of this series (Cohen 1999, hereafter Paper I), I presented an overview of this subject and the historical background for the present work, which began with the study of the giants in M13 by Suntzeff (1981). To summarize very briefly, star-to-star variations in several light elements, particularly C and N, are seen on the giant and subgiant branches of many globular clusters. The behavior of these variations within those globular clusters studied in most detail are in many cases consistent with what is expected for mixing as the explanation for most of the observed variations. 47 Tuc was the only Galactic globular cluster studied at the level of the main sequence, where mixing should not yet have occurred, yet Cannon et al. (1998) and references therein find detectable variations in the CH and CN bands for main-sequence stars in 47 Tuc, and these variations are anticorrelated.

Globular cluster main-sequence stars should not yet have synthesized through internal nuclear burning any elements heavier than He (and Li and Be) and hence will be essentially unpolluted by the internal nuclear burning and production of various heavy elements that occur in later stages of stellar evolution. Theory predicts that these stars are unaffected by gravitational settling and that their surfaces should be a fair representation of the gas from which the globular cluster formed. Thus the persistence of variations in C and N to such low luminosities in 47 Tuc (Cannon et al. 1998 and references therein) is surprising. The major recent reviews in this area are those of Kraft (1994) and Briley, Hesser, & Smith (1994), while the more general reviews of McWilliam (1997) and of Pinnsoneault (1997) are also relevant.

In Paper I, I analyzed spectra of 50 stars at or below the main-sequence turnoff in M13. I did not find any detectable variation in the strength of the CN or CH features in this sample. However, M13 is a quite metal-poor globular cluster, and hence here I present an analysis of the spectra of

79 stars on the main sequence of M71, a globular cluster with metallicity comparable to that of 47 Tuc.

2. THE SAMPLE OF STARS

M71 was chosen as the second cluster in this study because of its metallicity (Cohen 1983) and because it is nearby; hence the turnoff stars will be relatively bright. This globular cluster is located at Galactic latitude $b = -4.6^\circ$ and has a reddening $E(B - V) = 0.27$ mag (Reed, Hesser, & Shawl 1988).

Short-exposure images in B and R were taken with the Low Resolution Imaging Spectrograph (LRIS, Oke et al. 1995) at the Keck Observatory centered on the cluster. Photometry was obtained with DAOPHOT (Stetson 1987) using these short exposures calibrated on the system of Landolt (1992). The zero point for each color is uncertain by ± 0.05 mag. A sample of main-sequence stars was chosen based on their position on the locus of the main sequence as defined by this photometry. Each candidate was inspected for crowding and stars were chosen for the spectroscopic sample on the basis of minimum crowding. Table 1 gives the object's coordinates (B1950.0), R mag, $B - R$ color, and indices (together with their errors) for two molecular bands, the G band of CH at 4305 Å and the CN band near 3880 Å, for the M71 main-sequence stars in the spectroscopic sample. The magnitudes and colors given in Table 1 have not been corrected for extinction.

Since the fields are very crowded, in addition to providing the star coordinates, we provide an identification chart (Fig. 1) for a few stars in the M71 sample, from which, given the accurate relative coordinates, the rest of the stars can be located. Relative stellar coordinates are defined from the LRIS images themselves assuming the telescope pointing recorded in the image header is correct and taking into account the optical distortions in the images. The astrometry of Cudworth (1985) is used to fix the absolute coordinates.

Figure 2 presents a color-magnitude diagram for the main-sequence stars in the M71 sample. The stars that have been observed spectroscopically are displaced by -0.6 mag in $B - R$ color and are shown as filled circles.

The color-magnitude diagram of the field of M71 shown in Figure 2 reflects the low Galactic latitude this cluster. There are many field stars, most redder and presumably more distant than the globular cluster itself. Because the

¹ Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

TABLE 1
PROPERTIES OF THE SAMPLE OF MAIN-SEQUENCE STARS IN M71

ID	R (mag)	$B-R$ (mag)	$I(\text{CH})$ (%)	$\sigma(\text{CH})$ (%)	$I(\text{UV CN})$ (%)	$\sigma(\text{UV CN})$ (%)
M71ms 1951272 + 183732	17.12	1.29	0.158	0.004	0.165	0.010
M71ms 1951215 + 183720	17.00	1.38	0.167	0.005	0.165	0.009
M71ms 1951216 + 183611	17.52	1.28	0.078	0.003	0.205	0.008
M71ms 1951222 + 183914	17.47	1.34	0.109	0.003	0.252	0.009
M71ms 1951224 + 183638	17.60	1.39	0.086	0.004	0.225	0.010
M71ms 1951237 + 183746	17.17	1.39	0.174	0.005	0.136	0.008
M71ms 1951252 + 183722	17.01	1.31	0.152	0.005	0.160	0.009
M71ms 1951257 + 183914	17.21	1.40	0.114	0.004	0.260	0.008
M71ms 1951262 + 183856	17.57	1.32	0.152	0.005	0.149	0.012
M71ms 1951266 + 183825	17.39	1.28	0.130	0.004	0.166	0.013
M71ms 1951266 + 183940	17.35	1.36	0.135	0.004	0.178	0.010
M71ms 1951268 + 183621	17.37	1.28	0.149	0.004	0.145	0.011
M71ms 1951274 + 183641	17.44	1.30	0.117	0.003	0.178	0.007
M71ms 1951274 + 184033	17.35	1.38	0.161	0.005	0.176	0.011
M71ms 1951275 + 184023	17.53	1.30	0.132	0.004	0.176	0.010
M71ms 1951276 + 183751	17.49	1.23	0.151	0.004	0.139	0.009
M71ms 1951279 + 183947	17.54	1.42	0.169	0.006	0.155	0.013
M71ms 1951286 + 184144	17.57	1.28	0.103	0.003	0.232	0.009
M71ms 1951302 + 184144	17.44	1.30	0.150	0.005	0.141	0.011
M71ms 1951303 + 183943	17.26	1.29	0.086	0.003	0.253	0.008
M71ms 1951318 + 184025	17.38	1.28	0.142	0.005	0.146	0.011
M71ms 1951339 + 184038	17.15	1.31	0.163	0.004	0.147	0.007
M71ms 1951365 + 183958	17.25	1.34	0.151	0.004	0.145	0.006
M71ms 1951380 + 184103	17.52	1.27	0.165	0.004	0.185	0.005
M71ms 1951388 + 184119	17.32	1.32	0.143	0.003	0.107	0.007
M71ms 1951399 + 184126	17.43	1.27	0.097	0.002	0.182	0.007
M71ms 1951231 + 183740	17.47	1.35	0.142	0.005	0.142	0.013
M71ms 1951293 + 183721	17.19	1.32	0.143	0.006	0.146	0.014
M71ms 1951294 + 183804	17.59	1.28	0.142	0.005	0.136	0.012
M71ms 1951295 + 183748	17.26	1.27	0.123	0.005	0.255	0.009
M71ms 1951301 + 183738	17.01	1.34	0.121	0.005	0.266	0.009
M71ms 1951321 + 183715	17.40	1.29	0.133	0.005	0.173	0.010
M71ms 1951325 + 183607	17.55	1.28	0.137	0.004	0.154	0.009
M71ms 1951360 + 183614	17.17	1.31	0.174	0.004	0.135	0.009
M71ms 1951211 + 184010	17.35	1.31	0.145	0.005	0.144	0.012
M71ms 1951239 + 184109	17.39	1.39	0.099	0.003	0.243	0.009
M71ms 1951266 + 184102	17.49	1.36	0.139	0.004	0.140	0.012
M71ms 1951230 + 184200	17.43	1.35	0.095	0.003	0.220	0.008
M71ms 1951239 + 183906	17.46	1.29	0.098	0.003	0.251	0.008
M71ms 1951241 + 183940	17.14	1.42	0.181	0.006	0.160	0.010
M71ms 1951247 + 184144	17.13	1.40	0.130	0.004	0.281	0.007
M71ms 1951248 + 184155	17.36	1.32	0.141	0.004	0.175	0.009
M71ms 1951249 + 183857	17.42	1.33	0.146	0.005	0.159	0.013
M71ms 1951253 + 183831	17.13	1.36	0.124	0.005	0.253	0.008
M71ms 1951253 + 184132	17.24	1.34	0.123	0.005	0.244	0.008
M71ms 1951254 + 184008	17.25	1.35	0.158	0.005	0.160	0.011
M71ms 1951264 + 183933	17.20	1.34	0.117	0.004	0.243	0.009
M71ms 1951277 + 183627	17.33	1.36	0.203	0.008	0.314	0.012
M71ms 1951278 + 183638	17.05	1.33	0.162	0.006	0.245	0.010
M71ms 1951283 + 183952	17.48	1.25	0.131	0.005	0.173	0.012
M71ms 1951297 + 183832	17.39	1.29	0.146	0.006	0.136	0.011
M71ms 1951299 + 183617	17.03	1.35	0.203	0.008	0.298	0.010
M71ms 1951311 + 183525	17.45	1.38	0.187	0.007	0.324	0.010
M71ms 1951323 + 183552	17.55	1.23	0.099	0.004	0.230	0.008
M71ms 1951385 + 183741	17.54	1.24	0.139	0.004	0.147	0.009
M71ms 1951387 + 183512	17.16	1.31	0.157	0.004	0.126	0.007
M71ms 1951389 + 183610	17.55	1.30	0.141	0.004	0.145	0.007
M71ms 1951392 + 183732	17.45	1.24	0.090	0.003	0.227	0.007
M71ms 1951403 + 183817	17.22	1.31	0.152	0.004	0.158	0.007
M71ms 1951411 + 183806	17.15	1.31	0.098	0.003	0.231	0.008
M71ms 1951333 + 184107	17.24	1.39	0.189	0.006	0.272	0.009
M71ms 1951364 + 183720	17.26	1.25	0.128	0.004	0.149	0.009
M71ms 1951364 + 183749	17.42	1.29	0.133	0.005	0.137	0.010
M71ms 1951372 + 183945	17.30	1.24	0.135	0.004	0.145	0.009

TABLE 1—*Continued*

ID	<i>R</i> (mag)	<i>B</i> − <i>R</i> (mag)	<i>I</i> (CH) (%)	σ (CH) (%)	<i>I</i> (UV CN) (%)	σ (UV CN) (%)
M71ms 1951372+184149	17.01	1.40	0.126	0.004	0.296	0.007
M71ms 1951373+183642	17.21	1.28	0.152	0.005	0.138	0.007
M71ms 1951378+183706	17.52	1.26	0.097	0.004	0.230	0.007
M71ms 1951383+184003	17.11	1.33	0.170	0.006	0.267	0.007
M71ms 1951391+183901	17.25	1.35	0.140	0.004	0.140	0.010
M71ms 1951396+184028	17.56	1.28	0.146	0.004	0.146	0.007
M71ms 1951400+184016	17.14	1.27	0.122	0.003	0.214	0.006
M71ms 1951403+184120	17.51	1.39	0.186	0.005	0.216	0.008
M71ms 1951404+183926	17.05	1.41	0.197	0.005	0.138	0.005
M71ms 1951405+184141	17.03	1.36	0.125	0.004	0.268	0.007
M71ms 1951406+183826	17.59	1.29	0.108	0.003	0.226	0.005
M71ms 1951406+183853	17.03	1.38	0.148	0.004	0.265	0.006
M71ms 1951417+183631	17.29	1.34	0.103	0.003	0.218	0.005
M71ms 1951355+184057	17.18	1.31	0.094	0.003	0.227	0.008

radial velocity of M71 is -27 km s^{-1} (Cohen 1980), it is not possible to isolate a sample of cluster members using radial velocity measurements from low-dispersion spectra. My sample will therefore have some field star contamination. To estimate the fraction of field stars in such a sample, Figure 3 shows a histogram in color of all stars with $17.3 \text{ mag} < R < 17.6 \text{ mag}$. The sharp rise at the blue end of the distribution arises from the cluster, while the extended tail to the red is from field stars.

The M13 main sequence shown in Paper I is very narrow in color. Some of the apparent spread in color seen in the case of M71 may be due to variations in reddening. These are easily detected at the level of $\sim 25\%$ of $E(B-V)$ (and corresponding amounts in other colors) from multicolor photometry of stars on the red giant branch in more heavily reddened Galactic globular clusters (Cohen & Sleeper 1995). In addition, the field of M71 is very crowded, even more so than either of the two fields in M13 studied in Paper I. This may lead to photometric errors that might produce an apparent spread in color of the M71 main sequence.

Based on Figure 3 one might estimate a field star contamination that at worst does not exceed 25% of the sample.

3. SPECTROSCOPIC OBSERVATIONS AND MEASUREMENT OF BAND INDICES

Three slit masks were designed containing 79 stars from the M71 main-sequence star sample. These were used at relatively low dispersion with the LRIS (300 groove mm^{-1} grating, $2.46 \text{ \AA pixel}^{-1}$, $0''.7$ slit width) for a spectral resolution of $8 \text{ \AA}$. The CCD detector is digitized at $2 e^- \text{ DN}^{-1}$ with a readout noise of $8 e^-$. Two 800 s exposures were taken with each slit mask under conditions of good seeing and dark sky in the summer of 1998. The data were reduced in a straightforward manner as described in Cohen et al. (1999) using FIGARO (Shortridge 1988) except that the wavelength calibration came from arc lamp exposures, rather than from night-sky lines on the spectra themselves. The spectra are not fluxed.

The definition of the CH and UV CN indices measuring the strength of the G band of CH at $4305 \text{ \AA}$ and of the CN band at $3885 \text{ \AA}$ follows that of Paper I (Cohen 1999), except that the wavelengths are shifted to take into account the difference in mean radial velocity between M13 and M71.

The CH index again uses continuum bandpasses on both sides of the G band, with a feature bandpass chosen to avoid $\text{H}\gamma$. The CH and UV CN indices thus measured, together with their 1σ errors calculated assuming Poisson statistics, are given in Table 1. The values are the fraction of absorption from the continuum and are not in magnitudes. Recall that the errors given in Table 1 do not include the effect of cosmic rays or the effect of the background signal from the night sky, both of which are small.

The M71 main-sequence stars in my sample are somewhat brighter than those of M13, and the spectra are thus of even higher signal-to-noise ratio than those of my main-sequence sample in M13. Illustrative examples of the latter are shown in Figure 3 of Paper I.

The continuum level in one star of the 79 in the M71 main-sequence sample fell slightly below the minimum value ($700 \text{ DN pixel}^{-1}$) set in Paper I for accepting the UV CN index measurements. However, the features are so much stronger in this globular cluster that even the value for this object was accepted.

4. ANALYSIS

Figure 4 shows the CH index plotted as a function of R mag for the 79 stars in my M71 main-sequence sample. The 1σ error bars are shown for each star. It is immediately clear that there is a large range in CH strength at all luminosities whose range is many times the measurement uncertainties.

Four of the stars in my M71 sample have very strong CH for their magnitude and are believed to be field stars. They are indicated by crosses and are the only objects within the rectangle at the top right of the figure. Ignoring these four stars, a second-order least-squares fit was carried out of CH index as a function of R mag. Objects that lie above the mean fit are shown in Figure 4 as open circles, while objects that lie below this curve are shown as filled circles.

Ignoring the four probable field stars, the distribution of CH indices now appears to be approximately bimodal for the M71 sample.

Figure 5 show the results for the UV CN indices in the 79 M71 main-sequence stars, again plotted as a function of R mag. As was the case for the CH band indices, a large range in the strength of the UV CN band at a fixed luminosity is seen for the M71 main sequence. The overall appearance of the distribution is that it is bimodal. The same symbols are

FIG. 1.—Square section $110''$ on a side located slightly west of the center of M71 from a 3 s *B* exposure taken with LRIS. The positions of several M71 main-sequence stars in our sample in this field are indicated.

used in Figure 5 as in Figure 4. Comparing the two figures, it is immediately apparent that the CH and UV CN indices are anticorrelated. There are approximately equal numbers of CH-strong/CN-weak and CH-weak/CN-strong stars. Langer, Suntzeff, & Kraft (1992) find this fraction determined from spectra of the red giants to vary from cluster to cluster among a set of three Galactic globular clusters (M3, M13, and M79) of intermediate metallicity.

The good correlations seen in Figures 4 and 5 provide evidence that my M71 main-sequence sample is not seriously contaminated by field stars.

5. DISCUSSION

In Paper I, I showed that my data provide no evidence for variations of CH or CN band strengths among the 50 main-sequence stars in our sample in M13. Here in the case of M71 I have found a range in CH and UV CN indices at a given luminosity along the M71 main sequence that is much larger than the measurement errors. Furthermore, the CH and UV CN indices are anticorrelated, and both appear to be bimodal.

It may well be that even though the measurement errors

FIG. 2.—Color-magnitude diagram for the region of the main sequence in M71. The stars in our spectroscopic sample are shown as filled circles and are offset 0.6 mag to the blue in color.

in M13 are small, the low metallicity of the cluster and the definition of such relatively crude molecular band indices conspire to hide any variation that may actually be present. The next paper in this series (Briley & Cohen 1999) will explore this possibility and will attempt to provide a guess as to the range of C and N variations that may be present in each of the two globular clusters, M71 and M13.

The next step will be to analyze other light elements in M71 to see whether variations along the main sequence can be detected in Na, Ca, or Mg, for example. Na, and to a

FIG. 3.—Histogram in color of the 643 stars in the field of M71 with $17.3 \text{ mag} < R < 17.6$ is shown.

FIG. 4.—CH indices for 79 main-sequence stars in M71 are plotted as a function of R mag. The error bars shown for each point are 1σ errors calculated from the observed count rates assuming Poisson statistics. The symbol coding is discussed in the text.

lesser extent Mg, are known to vary among the giants and subgiants in several globular clusters. Suitable data from the LRIS at the Keck Observatory consisting of spectra of significantly higher dispersion than those analyzed here or in Paper I are already in hand for both the M71 and the

FIG. 5.—UV CN indices for 79 main-sequence stars in M71 are plotted as a function of R mag. The error bars shown for each point are 1σ errors calculated from the observed count rates assuming Poisson statistics. The symbol coding is the same as that of Fig. 4.

M13 sample. These spectra can also be used to eliminate at least some of the field stars in the M71 sample through radial velocities.

Now that it is clear that variations of C and N are strong in at least two metal-rich Galactic globular clusters at the level of the main sequence, a major effort needs to be mounted to differentiate between mixing and primordial variations. Understanding the origin of these star-to-star variations at the level of the main sequence is an issue of importance not only to the field of globular cluster studies but also has ramifications throughout many areas of stellar evolution and galaxy halo ages. I will return to this issue in future papers in this series.

6. SUMMARY

I have determined the strength of the CH and CN bands from spectra of 79 main-sequence stars in M71. Significant variations in the strength of the G band of CH at 4305 Å and of the UV CN band at 3885 Å are seen from star to star at a fixed luminosity on the main sequence of M71. Both the CH indices and the UV CN indices appear to be bimodal, and they are anticorrelated. There are approximately equal

numbers of CN-weak/CH-strong and CN-strong/CH-weak main-sequence stars in M71.

This is in contrast to the case of M13 discussed in Paper I, where no variations are seen for C and N in M13 at the level of the main-sequence turnoff and below it. I suggest that the variations may actually be present in M13 but cannot be detected with the molecular band indices I am using due to the low metallicity of M13 and to the lack of sensitivity of the molecular band indices themselves. It is not yet clear whether the origin of this behavior is due to mixing or to primordial variations or to some combination of these two factors.

The entire Keck/LRIS user community owes a huge debt to Jerry Nelson, Gerry Smith, Bev Oke, and many other people who have worked to make the Keck Telescope and LRIS a reality and to operate and maintain the Keck Observatory. We are grateful to the W. M. Keck Foundation, and particularly its late president, Howard Keck, for the vision to fund the construction of the W. M. Keck Observatory. I also thank Kevin Richberg for help with the data reduction

REFERENCES

- Briley, M. M., Hesser, J. E., & Smith, G. H. 1994, *Canadian J. Phys.*, 72, 772
 Briley, M. M., & Cohen, J. G. 1999, in preparation
 Cannon, R. D., Croke, B. F. W., Bell, R. A., Hesser, J. E., & Stathakis, R. A. 1998, *MNRAS*, 298, 601
 Cohen, J. G. 1980, *ApJ*, 241, 981
 ———. 1983, *ApJ*, 270, 654
 ———. 1999, *AJ*, 117, 2428 (Paper I)
 Cohen, J. G., & Sleeper, E. C. 1995, *AJ*, 109, 242
 Cohen, J. G., Hogg, D. W., Pahre, M. A., Blandford, R., Shopbell, P. L., & Richberg, K. 1999, *ApJS*, 120, 171
 Cudworth, K. M. 1985, *AJ*, 90, 65
 Kraft, R. P. 1994, *PASP*, 106, 553
 Landolt, A. U. 1992, *AJ*, 104, 340
 Langer, G. E., Suntzeff, N. B., & Kraft, R. P. 1992, *PASP*, 104, 523
 McWilliam, A. 1997, *ARA&A*, 35, 503
 Oke, J. B., et al. 1995, *PASP*, 107, 307
 Pinnsoneault, M. 1997, *ARA&A*, 35, 557
 Reed, B. C., Hesser, J. E., & Shawl, S. J. 1988, *PASP*, 100, 545
 Shortridge, K. 1988, *FIGARO User's Manual* (Starlink User Note 86) (version 2.4; Chilton: Rutherford Appleton Lab.)
 Stetson, P. B. 1987, *PASP*, 99, 191
 Suntzeff, N. B. 1981, *ApJS*, 47, 1